Using three different approaches of OSL for the study of young fluvial sediments at the coastal plain of the Usumacinta–Grijalva River Basin, Southern Mexico

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ABSTRACT: We use three different approaches of optically stimulated luminescence (OSL) to study young fluvial sediments located at the main channels of one of the largest fluvial systems of North America: the Usumacinta–Grijalva. We use the Pulsed Photo-Stimulated Luminescence (PPSL) system also known as portable OSL reader, full OSL dating and profiling OSL dating in samples extracted from vertical sediment profiles (*n* = 9) of riverbanks to detect changes in depositional rates of sediments and to obtain the age of the deposits. The results of the PPSL system show that the luminescence signals of vertical sediment profiles highly scattered from the top to the bottom contrast with the luminescence pattern observed on well–reset sequences of fluvial deposits where luminescence increase from the top to the

bottom of the profile. The profiling and full OSL ages yielded large uncertainty values on their ages. Based on the inconsistencies observed in both ages and luminescence patterns of profiles we suggest that these fluvial deposits were not fully reset during their transport. As an explanation, we propose that in the Usumacinta and Grijalva rivers the cyclonic storms during the wet season promote the entrainment of large volumes of sediments due to high-erosional episodes around the basin resulting from hyper-concentrated and turbid flows. We conclude that the PPSL, profiling and full OSL dating of sediments are useful tools to quantify and to assess the depositional patterns in fluvial settings during the Holocene. These techniques also can yield information about sites where increases in the sediment load of rivers may produce poorly resetting of grains affecting the results of OSL dating.

Keywords: Fluvial sediments; OSL; PPSL system (portable OSL reader); Usumacinta–Grijalva River Basin; Mexico

Introduction

The optically stimulated luminescence (OSL) technique is based on the study of the luminescence emitted by mineral grains after their optical stimulation. Luminescence signals are measured in photons and result from the electromagnetic energy released when excited electrons trapped within imperfections of grain lattices or traps in the gap band return to less energetic positions of the valence band (Aitken, 1995). The process described occurs when grains are exposed to visible, or nearly close to visible wavelengths of

the electromagnetic spectrum or when grains are heated to temperatures higher than 400 °C.

In ideal situations for OSL dating, grains must be fully exposed to sunlight during their transport by air, water, and gravity or the grains may become heated at high temperatures. Under these conditions the electrons located at the traps return to the valence band. These grains become “reset”, or in other words, the clock is set to zero prior to their burial. It is during the burial time when natural radiation of sediments and/or soils causes the trapping of electrons within mineral grains producing the “charging” of grains with luminescence (Aitken, 1995; 1998). Thus, in a vertical sediment profile containing a sequence of well–reset deposits, where the oldest deposits are at the base of the profile and the youngest are on the top, the pattern of luminescence signals steadily decreases from the bottom to the top of the profile.

The pattern of luminescence previously described is common in some fluvial–dominated landscapes. Lomax et al., (2007) found that palaeodoses increase with depth in a profile of 4 m of sediments extracted from an aeolian dominated environment located at the western sector of the Murray River Basin, Australia. Muñoz-Salinas et al., (2011; 2014) and Portenga and Bishop (2015) reported a case in the Lachlan River, Australia (see Fig. 1A), where the sediments sampled at the bottom of the profile contained more luminescence than those extracted from the top of the profile. Usually, in settings where sediments are well-reset, most of the equivalent doses from different aliquots,

which are needed for the full OSL dating, are within 2 standard deviations (Duller, 2008). This low scatter is shown in the case of the samples WEH1-1, WEH2-1 and WEH2-3 analysed in the work of Kunk et al., (2013). These samples were extracted from the fluvial deposits of one of the major rivers of Europe, the Elbe River in Northern Germany. For the case of the Lachlan River, Muñoz-Salinas et al., (2011; 2014) calculated an age with uncertainty of 2.43 ± 0.14 ka (SUTL2356) (see Fig. 2A).

There are sedimentary processes in which the luminescence signals in mineral grains deviate from the ideal situations previously described. This happens when the grains have not been completely exposed to sunlight during their transport resulting in a partially bleaching of these with some electrons remaining in their traps. In this case the grains are poorly reset and they contain an “inherited luminescence”. This process has been inferred from fluvial sediments of different sites (e.g., Galbraith et al., 1999; Duller, 2004; Brook et al., 2006). In this case, the inherited luminescence is stored in the grains and is subsequently added to next processes of electron trapping (Aitken, 1995; 1998; Singarayer et al., 2005). If the conditions described above predominate, the OSL age is overestimated (Duller, 2008).

In sites where mineral grains have not been fully reset, it is expected that the trend of the luminescence signals within a vertical sediment profile exhibit a weak correlation with depth or no correlation at all. This is the case analysed by Stang et al., (2012) in three vertical soil profiles of ~ 30 cm depth extracted

from poorly-sorted deposits that came from the denudation of a granitic batholith at San Gabriel Mountains, southern California, USA.

In an archaeological site located in cava Petrini, southern Italy, Sanderson and Murphy (2010) found that luminescence signals decrease with depth in a vertical sediment profile. This last case is unexpected because the oldest sediments are found as depth increases. The profile that these authors studied contained deposits transported by two different geomorphic processes: (1) rapid mass movement at the top between ~0-150 cm depth and (2) long-term soil development at the bottom between ~150-300 cm depth. Another case, in a lahar deposit resulting from a hyper–concentrated flow at the Popocatépetl volcano in central Mexico, Muñoz-Salinas et al., (2011) reported a random pattern of luminescence signals along a vertical sediment profile (see Fig. 1B).

In the case of poorly reset deposits, the equivalent doses of most of the aliquots are beyond 2 standard deviations (Duller, 2008). Therefore, errors are high for age values that end up being the OSL estimate. In a debris flow deposit in Gredos Gorge, central Spain, Muñoz-Salinas et al., (2013) reported an age and uncertainty of 10.7 ± 1.6 ka (SUTL2351; see Fig. 2B). For the case of Gredos, the uncertainty in the age of the deposit is considerable higher (1.6 ka) than the one calculated for the well-reset deposits studied at Lachlan River (i.e. sample: SUTL2356, uncertainty 140 years) (Muñoz-Salinas et al., 2013).

The examples cited above suggest that the luminescence of sediments may change according to the type of sediment transport. In this paper we study the

fluvial sediments of the Usumacinta and Grijalva rivers that together compose one of the largest fluvial systems of North America. We focus on the assessment of the fluvial deposits of the Holocene found at the margins of the main channel of rivers, in order to understand the recent sedimentation pattern and assuming that, because the setting corresponds to a fluvial–dominated landscape, the grains are probably well–reset like those previously described for the ideal situations for OSL dating (see Fig. 1A and 2A). Our assumption of finding well-reset grains for the young fluvial deposits of Usumacinta and Grijalva rivers in the floodplain is based on the hypothesis that (1) the grains may have been fully exposed to sunlight during their transport because there is a large distance from the headwaters to the floodplain and (2) since in tropical landscapes the sunlight exposure is high for long hours and there are high rates of solar radiation, the grains are likely to be set to zero prior to their burial time.

In this study we exploited the OSL technique using three different approaches: (1) the application of a Pulsed Photo-Stimulated Luminescence (PPSL) system, also known as portable OSL reader, (2) the full OSL dating and (3) the profiling OSL method. We use these three methods because these approaches allow (1) the dating of recent fluvial sediments and (2) the analysis of sediment transport based on the study of luminescence signals.

Study area

The rivers Usumacinta and Grijalva form a single river basin, however each river flows separately before joining just ~15 km off the coast of the Gulf of Mexico (Fig. 3). The headwater of each of the two rivers is located in Guatemala (Hudson et al., 2005) and they mostly flow in the southern part of Mexico, crossing the States of Chiapas and Tabasco. The Grijalva River has a total length of ~640 km and the Usumacinta River is ~1100 km (Day et al., 2003). The Usumancinta and Grijalva river basin (UGRB) is the largest fluvial system of Mexico and it is placed in the number 10^{th} of the ranking of the major rivers of North America (Benke, 2009). The total discharge of the UGRB is ~2,678 m^3s^{-1} and its basin area is of ~112,000 km^2 (Benke, 2009).

Two main geomorphological units characterize the UGRB: (1) The coastal plain located at the lowlands and (2) the mountain area located at the highlands (Hudson et al., 2005) (Fig. 3). In the first unit a low relief area consisting of wetlands forms the wide coastal plain of the Gulf of Mexico (Benke, 2009) and extends from the coast to ~120 km inland. The main lithology of this geomorphic unit is Cenozoic sediments and rocks. The sediments result from the denudation of the mountainous area. Along the coastal plain, the rivers have high sinuosity and the formation of meanders, oxbox lakes, and chute channels is common.

The second geomorphic unit is the mountain area which is composed by the Sierra de los Cuchumatanes, the Sierra Madre de Chiapas and the Altos de Chiapas. Between the Sierra Madre de Chiapas and the Altos de Chiapas it is the Depresión Central de Chiapas, which is a large karstic canyon of ~600 m

a.s.l. where the Grijalva River flows into (Fig. 3A). Cretaceous limestones and dolomites compose most of the Sierra de los Cuchumatanes (Marshall, 2007). The lithology of Sierra Madre de Chiapas is composed of diorites and granites belonging to a Paleozoic batholith (Cros et al., 1998; Morán-Zenteno et al., 1999). The Altos de Chiapas are constituted by Mesozoic sequences of marine and continental clastic–carbonate materials with the presence of some Cenozoic volcanic deposits (Morán-Zenteno et al., 1999) (Fig. 3B).

The mean annual rainfall in the UGRB exceeds 2 m. The high rates of rainfall in this region influence the water discharge around the basin producing large water and sediment discharge rates (Hudson et al., 2005; Muñoz-Salinas et al., 2015). Nevertheless, the spatial distribution of rainfall is highly variable in the UGRB. The climate in the lowlands and part of the Altos de Chiapas is tropical without the presence of a dry season (http://www.inegi.gob.mx, 2013). In the highlands some areas receive more than 6 m of mean annual rainfall (http://www.conagua.gob.mx, 2013). The Inter-Tropical Convergence Zone generates an intense rainfall season that starts in May and ends in October. The drier season takes place from November to April (Grodsky and Carton, 2003). At the UGRB, convective clouds and tropical cyclones prevail during the summer season. The heavy rainfalls produce the rapid increase in water discharges at the Usumacinta and Grijalva rivers causing the flooding of the lowlands (Rosengaus-Moshinsky et al., 2002).

The distribution of the vegetation in the UGRB is controlled by the topographic gradient, which in turn, is related to the amount of rainfall and changes in

temperature gradient. The rapid change of elevation in just a few kilometers produces contrasting biophysical sites (Weibel, 1998). The main Eco–regions in the basin are composed by mangrove swamps and marshes in the coastal plain of the lowlands (Reyes et al., 2004) and tropical to subtropical forest in the highlands (Hudson et al, 2005; Ramírez-Marcial et al., 2001).

The UGRB has a long history of occupation that can be traced back to the Olmec Civilization that started around the 18th Century B.C. (Hirth et al., 2013). After the Olmecs, the Maya Civilization developed a complex system of land occupation during the Classic Period, which started from the 3rd Century B.C. and ended in the 9th Century A.D. After the collapse of the Maya Empire, the environment of the UGRB was slightly modified until the 20th Century (Zebadua, 1999), when deforestation rates around the UGRB became one of the highest around the world (Benjamin, 1981; Ochoa-Gaona and González-Espinosa, 2000).

The control of the water flow of the Grijalva River started in 1964 A.D. with the construction of the Netzahualcóyotl dam, which is the second largest dam of Mexico; capturing 10x10^4 m^3 of fresh water. The Belisario Dominguez dam was build in 1978, also in the Grijalva River, and captures 15x10^4 m^3 of fresh water, being the largest dam of Mexico (http://www.conagua.gob.mx, 2013). The Usumacinta River is undammed.

Methodology

We use the PPSL unit, which has been recently proposed in the study of fluvial processes (Sanderson and Murphy, 2010; Muñoz-Salinas et al, 2011), to compare the luminescence signals of nine vertical sediment profiles extracted at the floodplains of the Usumacinta and Grijalva rivers with the ideal trend of well-reset deposits previously described. The goal is to assess if the grains of the fluvial deposits in these two rivers are well-reset, as hypothesized (Fig. 3) and, therefore, OSL can be used to establish a chronology of recent fluvial events.

The full OSL dating method is based in the conventional OSL dating protocol that use the Single-Aliquot Regenerative (SAR) method, which is used here in order to obtain the age of deposits selected at different depths of four different profiles. The profiling OSL dating is less accurate than the full OSL dating to obtain ages in sediments, in which only the equivalent doses are calculated for the samples. The dose rates in the profiling OSL dating are estimated from sites adjacent to the full OSL dating sites. In the profiling dating it is assumed that the sediment has similar radiation dosimetry than the sediment sampled for the full OSL dating method. We performed the profiling OSL at different depths of the four profiles selected to for the full OSL dating, since the dose rates calculated for the later are also used for the profiling.

Sample extraction during fieldwork

The samples analysed in this study were extracted at different depths of profiles composed by the deposits abandoned by the Usumacinta and Grijalva

rivers during the flooding of the overbanks. The sequence of these flood deposits can be recognized in the slopes located at the inner part of the main channel of the rivers, just where the water flow is regularly confined into the channel during the low flow stage. During the wet season, the water flow eventually raises above the main channel and inundates the overbanks. When this last situation of high flow stage takes place, the sediment transported by rivers is deposited on the surface of the overbanks and therefore, the overbanks contain valuable information about the most recent flood events (Fig. 4). The vertical sediment profiles in this study were selected only at the erosive margins of channels in order to avoid the sampling of the sediment remobilized by slope slides at the depositional margins (Fig. 4). Moreover, we avoided the sites with any visible sign of bioturbation caused by either animals or humans. To obtain the samples we performed two fieldwork campaigns that were carried out during the winter season (the first one in April 2012 and the second one in February 2013).

We sampled a total of nine profiles, five at the Usumacinta River named USU1, USU2, USU3, USU13-1 and USU13-2, and four at the Grijalva River, coded GRIJ-PA1, GRIJ-PA2, GRIJ-PB1 and GRIJ-PB2. In all of the nine profiles we extracted samples for measuring the luminescence using the PPSL approach. We extracted samples for full OSL dating and OSL profiling in only three profiles of the Usumacinta River (USU2, USU13-1 and USU13-2) and in one profile of the Grijalva River (GRIJ-PA1; Fig. 5).

We performed the sampling of profiles during daylight. In order to prevent the bleaching of the material during its extraction, we covered the profiles with a thick black plastic cloth to darken the surface of the profile. Once covered the surface, we introduced ourselves underneath the cloth and we removed ~5 mm of the outer material of the profile to avoid the sampling of sediment exposed to sunlight. Next, we placed a measure tape oriented from top to bottom next to the profile in order to reference the depths from the top where samples were extracted. For the PPSL and the profiling OSL dating, samples were extracted using pvc cylinders of ~3 cm long with ~1 cm of diameter and for the full OSL dating we used pvc cylinders of ~20 cm long and ~5 cm of diameter. Once we extracted the sediment from the profiles using the cylinders, these were wrapped using aluminium foil still inside of the cloth. The cylinders were labelled with their respective code and depth. After labelling, ~200 g of the sediment was extracted from the periphery of the samples selected for the full OSL dating. The material was placed in small bags and labelled according to their assigned codes.

PPSL analysis

To measure the luminescence signals coming from the samples extracted at the UGRB we used the PPSL unit build at the Scottish Universities Environmental Research Centre (SUERC), UK. The analyses were performed at the Irradiation Unit of the Research Institute of Nuclear Sciences of the *Universidad Nacional Autónoma de México,* Mexico. The Infra–Red Stimulated Luminescence (IRSL) is the optical stimulation available at the PPSL reader

and that was used to stimulate the samples. The PPSL unit has a photomultiplier with U–340 detection filters to measure the Anti-Stokes luminescence received from the stimulated samples that generates photons detected and quantified with high sensitivity using a digital lock-in photon counting method. A total of 130 samples were analysed with the PPSL from the nine profiles selected in fieldwork (i.e. USU1, USU2, USU3, USU13-1, USU13-2, GRIJ-PA1, GRIJ-PA2, GRIJ-PB1 and GRIJ-PB2).

The material analysed contained ~5 grams of polymineral and polygrain–size sediments. In laboratory, the samples were processed under safe red light to avoid any bleaching of grains at their preparation and subsequent reading. The samples were not chemically treated and were not sieved before being placed in petri-dishes for their stimulation in the PPSL unit. We followed the procedures described by Sanderson and Murphy, (2010) and Muñoz-Salinas et al., (2011; 2014).

Full OSL dating

The full OSL dating method consists of obtaining equivalent doses and dose rates for calculating the age of the deposits (Aitken, 1995; 1998). A total of 8 samples were selected for applying the full OSL dating method. These are located at profiles USU2, USU13-1, USU13-2 and GRIJ-PA1. The samples were sent to the SUERC laboratory in UK.

In the laboratory, all samples were handled under safelight conditions. Samples from the Grijalva River (profile GRIJ-PA1) were labelled as SUTL numbers 2508 and 2509. Samples from the Usumacinta River were labelled depending on the profile as: (1) USU2 with the codes of SUTL numbers 2511, 2512 and 2513, (2) USU13-1, with the numbers of 2580, and 2581 and (3) USU13-2, with the numbers of 2583, 2584, and 2585.

The SAR protocol was used in order to calculate the equivalent doses of samples since this protocol allows correcting changes in sensitivity in the luminescence signals (Murray and Roberts, 1998; Murray and Wintle, 2000; Kinnaird et al., 2012; 2014). To apply the SAR protocol, 16 aliquots were initially prepared for each sample. However, some aliquots did not yield equivalent doses and for some samples, more aliquots were prepared. Thus, the number of aliquots used for the calculation for the full OSL dating is different from sixteen (see Table 1). Each aliquot was placed in a stainless steel disc of ~10 mm mounted with ~200-300 grains of quartz in the fraction of 125-250 μm. For grain size selection, wet sieve between 125 and 250 μm was done. In order to dissolve less chemically resistant minerals and to etch the outer part of the grains and to obtain just grains of quartz, the samples were leached with 1M 40% HF for 40 minutes and 1M 40% ClH for 10 minutes. The remaining grains were centrifuged in sodium polytungstate solution to separate the quartz fraction from heavy metal grains. The selected quartz fraction was then subjected to further leaching with HF and HCl (1M 40% HF for 40 minutes, followed by 1M HCl for 10 minutes). All samples were dried at 50 °C and transferred to Eppendorf tubes.

The aliquots were placed in the carrousel of an automated Risø TL/OSL DA-15 that is equipped with: (1) diodes in the blue stimulation emitting around 470 nm and diodes in the infrared (laser) stimulation emitting around 830 nm for optical stimulation, (2) U-340 detection filters to detect in the region 270-380 nm and (3) an irradiation β-source Sr90/Y90 (Bøtter-Jensen et al., 2000). Regenerative dose responses curves were obtained using the natural readout and followed by cycles of readout after several irradiations of 1, 5, 10 and 20 Gy, with a test dose of 2 Gy. For equivalent dose determination, data from SAR measurements were analysed using the Risø TL/OSL Viewer programme to export integrated summary files that were analysed in MS Excel® and SigmaPlot®. Composite dose response curves and radial plots were constructed from selected discs. The radial plots indicated the mean, median, robust mean, logged and non-logged central age modelled mean of Galbraith et al., (1999). The robust mean was calculated by an MS Excel® add-in "robust statistics" available from the Chemistry Society of London, which calculates a robust mean using Huber's estimate 2.

Dose rates of irradiation were calculated using bulk quantities of the material extracted from the surrounding perimeter of the tube samples and it was measured using a high-resolution gamma spectrometer. In order to do the dose rate analysis, the material was placed in an oven to dry to constant weight. Approximately 100 g of the dried material from each sample was used for the high-resolution gamma spectrometry measurement. Gamma ray spectra were recorded over the 30 keV to 3 MeV range from each sample,

interleaved with background measurements and measurements from SUERC Shap Granite standard in the same geometries. Counting times of 80 ks per sample were used. The spectra was analysed to determine count rates from the major line emissions from ^{40}K (1461 keV), and from selected nuclides in the U decay series (^{234}Th, ^{226}Ra+^{235}U,^{214}Pb,^{214}Bi and ^{210}Pb) and thorium decay series (^{228}Ac,^{212}Pb,^{208}Tl) including their statistical counting uncertainties. Net rates and activity concentrations for each of these nuclides were determined relative to Shap Granite by weighted combination of the individual lines for each nuclide. The internal consistency of nuclide specific estimates for uranium and thorium decay series nuclides was assessed relative to measurement precision, and weighted combinations used to estimate mean activity concentrations (Bq kg^{-1}) and elemental concentrations (% K and ppm U, Th) for the parent activity. These data were used to determine infinite matrix dose rates for alpha, beta and gamma radiation (Kinnaird et al., 2012; 2014). To calculate the final dose rates, the cosmic dose rate contribution was calculated based in Prescott and Hutton (1994).

Profiling OSL dating

The profiling OSL dating method consists of obtaining apparent ages by using equivalent doses calculated for the sample and dose rates obtained not for the sample but for the adjacent full OSL dating sample extracted from the same sampling profile. Using the profiling OSL dating method it is assumed that the

sediment studied in the profile is similar in the radionuclide concentration. To perform the profiling OSL dating method it is necessary to firstly know the age via the full OSL dating method (Burbidge et al., 2007; Sanderson et al., 2007; Muñoz-Salinas et al., 2014). The profiling OSL dating analysis was also done at the SUERC laboratory in UK where all samples were managed under safelight.

We extracted 16 samples for the profiling OSL dating method in the same four profiles selected for the full OSL dating. In laboratory, these profiling samples were named with the code of the closest full OSL dating sample and followed by a letter. For the Grijalva River (profile GRIJ-PA1) samples were labelled as SUTL 2510A, 2510B and 2510C. Samples from the Usumacinta River were labelled depending on the profile as: (1) USU2 with the codes of SUTL 2514A, 2514B and 2514C, (2) USU13-1, with the codes SUTL 2581A, 2582B, 2582C, and 2582D and (3) USU13-2, with the numbers and letters 2586A, 2586B, 2586C, 2586D, 2586E and 2586F.

To calculate equivalent doses in the profiling OSL dating samples, two aliquots were prepared following the procedures described for the full OSL dating method. The SAR protocol was used to obtain luminescence signals, using the Risø TL/OSL. The total dose rate used for the profiling was estimated by extrapolating the dose rate trend through the closer full OSL dating locations or by taken directly the dose rate of the closest full OSL dating sample.

Results

PPSL system results

The luminescence values obtained from the nine sampling profiles of the UGRB do not exhibit a steady decrease of luminescence values from the bottom to the top as expected in the ideal situations for OSL dating when there is succession of well-reset deposits (Fig. 6). Instead, in all of the nine profiles the luminescence values show a random pattern resembling the succession of poorly reset deposits that deviate from the ideal situation for OSL dating (see for comparison the luminescence signals obtained for the sequence of lahar deposits at Popocatépetl volcano; Fig. 1B).

Full OSL dating results

The two samples located in the Grijalva River at profile GRIJ-PA1 (SUTL 2508 and 2509) show a variable equivalent dose distribution (Fig. 7). As a result, the ages obtained for these two samples have uncertainties of hundreds of years, as it can be observed in the resulting calendar years of 1120 ± 350 AD (SUTL2508) and 550 ± 270 AD (SUTL2509) (Table 2). There is progression of the two ages with depth since sample SUTL2508 at 0.49 m depth is younger (1120 ± 350 AD) than sample SUTL2509 at 1.36 m depth (550 ± 270 AD).

The eight samples located in the Usumacinta River, three at profile USU2 (SUTL2511, 2512 and 2513), two at profile USU13-1 (SUTL2580 and 2581) and three at profile USU13-2 (SUTL2582, 2583 and 2584) do not have a high scatter of palaeodoses compared with those samples observed for the Grijalva River (Fig. 8). The resulting ages in the Usumacinta River have uncertainties of decades (Table 2). In profiles USU2 and USU13-1, the resulting calendar years exhibit older ages at deeper parts of the profile, as expected. In profile USU13-2 the increase of age with depth occurs for samples SUTL2583 and 2584 but not for sample SUTL2585, what is located in the bottom of the profile.

Profiling OSL dating results

The equivalent doses obtained for the two aliquots for each profiling sample are presented in Table 3. From the profiling data (Table 3) it can be observed that in ten of the sixteen samples the difference between the two aliquots is greater than 1 Gy. The mean value of the equivalent doses obtained for aliquot 1 and 2 was used in the apparent age calculation presented in Table 2.

In profile GRIJ-PA1 the profiling ages are older with depth as was expected from our initial hypothesis. However if both the profiling and full OSL dating samples are considered for interpreting the whole profile, it can be observed that there is not a clear trend between the age and depth. The uncertainties of ages are of hundreds of years as was also the case for the full OSL dating ages for the Grijalva River.

In profile USU2 the profiling and full OSL ages show a scaling between the age and depth with exception of the sample located at the bottom of the profile (i.e., between 1.34 and 1.50 m depth). Sample SUTL2514C is apparently younger (AD 1490) than SUTL2513 (AD 1620). However the uncertainty of the age calculated for the profiling sample SUTL2514C is higher than for the full OSL sample SUTL2513. Apart from SUTL2514C that contains an uncertainty of more than a century, the rest of the ages in profile USU2 are within the order of decades. The profiling sample 2514B (AD 1620) was taken at the same depth of the full OSL dating sample SUTL2512 (AD 1670) however they have a difference of 50 years and the same uncertainty in their age.

In profile USU13-1 the profiling ages are older with depth as expected since the SUTL2582A at 0.2 m depth is, according to the results, older than SUTL2582B at 0.6 m depth. However, the ages including profiling and full OSL ages only have a good progression from 0.6 m to 1.4 m of depth. Most of the samples contain uncertainties of several decades, except for the two profiling samples at the top and the bottom that contain uncertainties of hundreds of years.

In profile USU13-2 the profiling and full OSL ages correlate with depth only in the first 1.25 m (see values in Table 2 and Fig. 5). Below the 1.5 m depth, ages have a random pattern. In profile USU13-2 there are some samples that

contain high uncertainties, such as sample SUTL2586D that has an uncertainty in the order of thousands of years.

Discussion

All the results obtained by the three different OSL methods indicate that the young fluvial sediments located in the floodplains of the Usumancinta and Grijalva rivers are incompletely reset. Such behaviour contrasts with our initial hypothesis. The PPSL signals of the nine profiles revealed an increase and decrease of luminescence at different depths of each profile (Fig. 6). Such a random luminescence trend versus depth was observed in poorly reset sediment profiles, as contrary to the progressive increase of luminescence from top to bottom in well–reset sediments (Fig. 1A).

The radial plots including the distribution of equivalent doses calculated for the aliquots prepared for the full OSL dating samples reveal that there is great variability of our data (Figs. 7 and 8). Also, the equivalent doses for the two aliquots prepared for most of the profiling samples show a large variability (Table 2).

The uncertainties calculated for the profiling and full OSL samples based in the equivalent doses and dose rates highlight the large uncertainty in the OSL ages which range from decades to hundreds of years and one of them with a thousands of years (Table 2).

Advantages and limitations in the three OSL methods

The PPSL analysis can be used as a proxy to the grade of resetting of sediment in a profile composed by a succession of deposits. Muñoz-Salinas et al., (2011; 2012; 2014) and Portenga and Bishop (2015) showed the usefulness in using the PPSL analysis to identify different depositional processes and sediment transport rates of grains in fluvial environments. We cited two types of scenarios of luminescence patterns. In the first one we presented the case of the deposits consisting of well–reset fluvial sediment of Lachlan River in Australia (Fig. 1A) and in the second one we presented the example of a poorly reset fluvial sediment in the Popocatépetl volcano (Fig. 1B). In the first case, the fluvial sediments were transported in dilute flows and in the second one, the fluvial sediments were mobilized in turbid and/or hyper–concentrated flows. The luminescence patterns observed in the nine profiles of the UGRB resemble the luminescence pattern observed in the lahar deposits of the Popocatépetl volcano. We postulate that hyper–concentrated transport may be a plausible explanation for the random pattern of luminescence detected on the deposits that compose the young fluvial sediment at the Usumacinta and Grijalva rivers. We propose that using the PPSL analysis is a reliable tool for detecting luminescence patterns in sediments that may be helpful to infer the flow conditions in which the sediment was transported. An increase in luminescence from the top of the deposit to the bottom would indicate a condition where the sediment was transported by flows that allowed the exposure of grains to sunlight. This situation usually occurs when grains

travel for large distances and/or grains are mobilized in clear water. In contrast, a random pattern in the luminescence with depth can be indicative of sediment mobilized in hyper–concentrated flows, where the grains are not fully exposed to sunlight due to turbidity or because grains were mobilized in a short time.

The application of the full OSL dating method is currently one of the more commonly used methods in many geomorphologic studies. The dating with OSL is a powerful geochronological tool for dating fluvial deposits, which can also provide information about the grade of resetting of the grains by interpreting the radial plots of equivalent doses and by setting their respective uncertainties. In the case of the Usumacinta and Grijalva rivers, the full OSL dating revealed a large variability of the equivalent doses, as a consequence, large uncertainties were obtained for the calculated ages.

The profiling OSL method is less applied than the full OSL method, since this first technique is less precise for the calculation of ages compared to the full OSL dating. Nevertheless, the dating with OSL profiling has lower costs than the full OSL dating and can be used to identify differences in depositional rates in fluvial landscapes. Muñoz-Salinas et al., (2014) used both the full OSL method and profiling for dating several deposits located at different depths in a well–reset succession of fluvial sediments in the Lachlan River in Australia. In that study, the ages in the profiling and full OSL samples revealed a good trend of luminescence versus depth. However, in the study of the Usumacinta and Grijalva rivers, the profiling method did not provide accurate ages.

Moreover, the approach revealed inconsistencies in the age of sediment. We postulate the use of OSL profiling is suitable only in sites were deposits contain well–reset sequences along the profiles. In order to prevent unnecessary expenses for either the full OSL dating and the profiling OSL method, the analysis using PPSL is here highly recommended before dating the sediment.

Poorly reset deposits in the recent fluvial sediments of the UGRB

In tropical areas the cyclonic activity is intensified during the summer periods but also the rate and magnitude of the cyclonic activity change every year (Grodsky and Carton, 2003). Therefore, intense stormy events (lasting from minutes to a few days) can promote intense episodes that can trigger hyper-concentrated and turbid flows (Beach et al., 2008; Rosengaus-Moshinsky et al., 2002). These kinds of flows are able to inundate the overbanks of channels and leave deposits containing grains that are unlikely to be bleached during their transport. In our study we focused in the analysis of samples abandoned overbank. We suspect that some of the sediments were deposited by turbid and hyper–concentrated flows that took place during rapidly eroding episodes on the river basin. Moreover, in large basins like the UGRB, the source of the grains deposited in the floodplains may be transported from close areas or from far distances, thus, a mixture of grains with different travel histories and resetting grades can be composing part of the deposits of the floodplain.

To explore the source of grains we have plotted the maximum PPSL luminescence values in the Usumacinta and Grijalva profiles versus the distance from the basin divide (Fig. 9). In Figure 9 it can be observed how luminescence values decrease within distance from the divide as grains are exposed to sunlight for longer periods of time. For the case of the Lachlan River (Muñoz-Salinas et al., 2014), the maximum luminescence values decrease with distance to the divide indicating that the main source of the material deposited by the river came from the mountain area (see in Fig. 9 the of R^2 = 0.56 of IR luminescence signals versus distance from divide). However, in the case of the Usumacinta and the Grijalva rivers the correlation is weak, suggesting that the sediment source may not be from far away (see in Fig. 9 that the correlation for the Grijalva River is of R=0.48 and for the Usumacinta River of R=0.14). We suggest that sediment at the floodplains of the Usumacinta and Grijalva rivers is partially connected in the river system and by hence, most of the sediment is stored at the floodplains of the rivers during some time and it can only be mobilized (and reconnected) during extreme flood events; as it is described by Hooke (2003). Therefore, grains at the floodplains of the Usumacinta and Grijalva rivers contain mixed reset histories that are highly likely responsible for the variability observed in the equivalent doses in the profiling and full OSL dating samples here.

The dose rates are also related to the luminescence signals as it was detected from the random values observed in the dose rates of the Grijalva and Usumacinta profiles (Table 2). The changes in the dose rates are conditioned by the amount of radionuclides contained in each deposit. In a large basin like

the UGRB in which the sediment source may be produced from different types of lithology (see Fig. 3B) and in which sediment can be eroded from different places of the riverbasin, the concentrations of radionuclides can have different concentration depending on the lithology.

Finally, even though the sedimentological processes described in this study may increase the errors and uncertainties in the ages calculated by the full OSL and profiling dating methods, most of the ages indicate that the sedimentation in the main channel of the Usumacinta and Grijalva rivers in the floodplain started during the Classic period of the Maya Civilization. Therefore the sedimentation observed in the main channels of the UGRB is less than two thousand years (see Table 2).

We minimized the impact of dams in the reset grade of the sediments studied here because: (1) the dams are only constructed in the Grijalva River and not in the Usumacinta River and we have either poorly reset sediment in the Grijalva and in the Usumacinta rivers and (2) the first dam was built in 1968 and the ages obtained for the samples are older than that age.

Conclusions

The three methods used in this research to study young fluvial sediments at the floodplains of the Usumacinta and Grijalva rivers strongly indicate that most of the grains deposited at the floodplain of the UGRB are partially bleached during their transport. The PPSL analysis allowed the detection of

luminescence patterns of incomplete reset deposits that may have been resulted from the transport of these by turbid and hyper–concentrated flows. The profiling and full OSL dating indicate that the sediment contains large variability in their equivalent doses resulting in large uncertainties on the calculated ages. Such variability explains errors from several decades to thousands in our samples of the Holocene. We propose that the use of the PPSL analysis is a powerful tool to detect poorly reset sequences of deposits. Such approach is useful in order to reduce the costs of OSL dating, especially in the profiling with OSL. We also conclude that the possible causes of the incomplete bleaching of the young sediments of the UGRB found at the floodplains is probably related to the cyclonic activity controlling the discharge of rivers in the basin which may be enhanced with high–magnitude cyclones producing turbid and hyper–concentrated flows.

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Figure captions

Figure 1. A. Profile of well–reset fluvial sediments at Lachlan River (Australia) where luminescence values (IRSL) increase with depth. Note the tight correlation where R^2=0.98 (modified from Muñoz-Salinas et al., 2011). B. Profile of poorly reset grains from a lahar deposit (i.e. turbid and hyper–concentrated flow) of the Popocatépetl volcano (Mexico). In this case there is a lack of correlation between the luminescence and depth. It is evident the random increase and decrease of luminescence with the depth (modified from Muñoz-Salinas et al., 2012).

Figure 2. Radial plots of equivalent doses. In A most of the values are within 2 standard deviations (i.e. fluvial deposits at Lachlan River, Australia; modified from Kinnaird et al., 2011a). In B most of the values are above 2 standard deviations (deposit of debris flow at Gredos Valley, Spain; modified from Kinnaird et al., 2011b). Sample SUTL2356 in A provided an age of 2.43 ± 0.14 ka with low uncertainty indicating that grains were well–reset and sample SUTL2351 in B has an age of 10.7 ± 1.6 ka estimated with high uncertainty and indicating that grains may have not been fully reset.

Figure 3. A Location of the Usumacinta and Grijalva rivers. The Grijalva River begins at the Sierra de los Cuchumatanes and flows down between the Sierra Madre de Chiapas and Altos de Chiapas incising both mountain settings. The Usumacinta Rivers also begins at the Sierra de los Cuchumatanes but flows down the northern sector of the Altos de Chiapas. These two rivers join just a

few kilometers inland. The white circles indicate the places where the profiles for OSL analysis where taken in the Coastal Plain. (B) Sketch map of the main lithological units of the UGRB.

Figure 4. Cartoon of a cross-section located at the main channel of the Usumacinta and Grijalva rivers at the Coastal Plain of the Gulf of Mexico. In the figure is shown a typical location in the main channel for the vertical sediment profiles selected for sampling. The sampling sites are located on the margins eroded by the river. We avoided the accumulative margins and sites containing material from slope slides and sampling profiles with evident signs of bioturbation.

Figure 5. The four selected profiles in which the full OSL dating method and the profiling OSL method were applied at Usumacinta River (USU3, USU13-1 and USU13-2) and at Grijalva River (GRIJ-PA1).

Figure 6. Luminescence signals versus depth for the nine PPSL profiles located at the floodplains of the Usumacinta and Grijalva rivers. Note that in the nine profiles the luminescence values increase and decrease at different depths in a way similar to those reported for the trend observed of the deposits of the Popocatépetl volcano (Fig. 1B).

Figure 7. Scatter plots of equivalent doses for the Grijalva samples (SUTL 2508 and 2509). Notice that the equivalent doses of most of the aliquots have more than 2 sigma values indicating poor reset of the grains.

Figure 8. Scatter plots of equivalent doses for the Usumacinta samples (SUTL 2511, 2512, 2513, 2580, 2581, 2583, 2584 and 2585). Notice that the equivalent doses of most of the aliquots have more than 2 sigma values indicating poor reset of the grains except for SUTL 2512 and 2590.

Figure 9. Plot of maximum IR luminescence signals for each sampling profile versus distance from divide. For comparisons are included the values published for the Lachlan River by Muñoz-Salinas et al., 2014.

Table 1. Number of aliquots used for full OSL dating calculations.

SUTL number	Number of aliquots
2508	16
2509	29
2511	15
2512	15
2513	20
2580	12
2581	16
2583	16
2584	16
2585	16

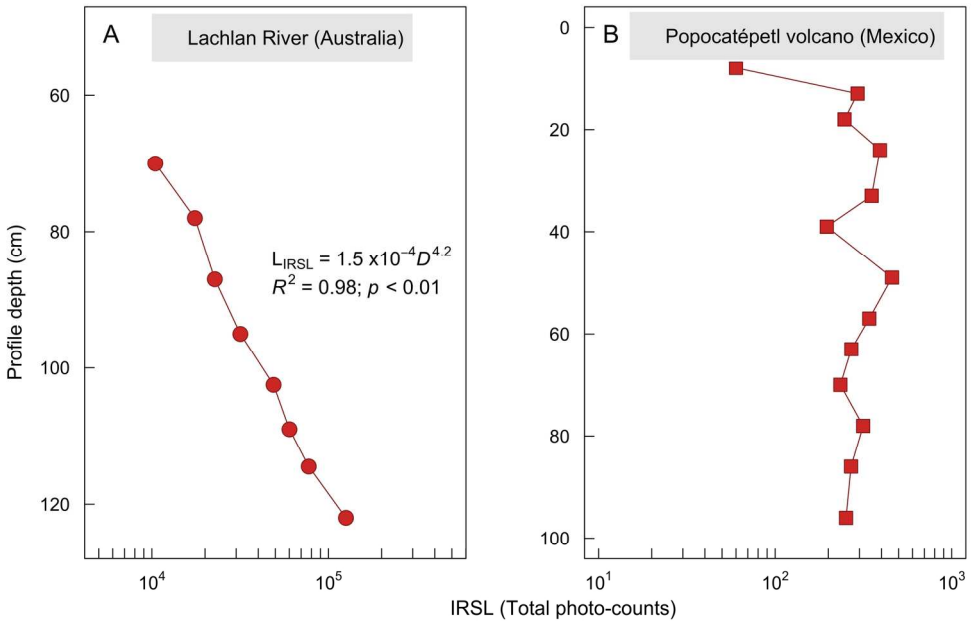
Table 2. OSL age determinations for samples at the Grijalva and Usumacinta rivers.

SUTL n°/ River/Profile	Depth (m)	Equivalent dose (Gy)	Dose rate (mGy a^{-1})	Calendar year (AD, unless stated otherwise)
River Grijalva				
GRIJ-PA1 (2012)				
2510A	0.18	6.51 ± 0.16	2.71 ± 0.16	390 ± 240
2508*	0.49	2.4 ± 0.94	2.69 ± 0.11	**1120 ± 350**
2510B	0.88	6.33 ± 1.31	2.66 ± 0.16	370 ± 510
2510C	1.18	4.96 ± 1.05	2.64 ± 0.15	130 ± 410
2509*	1.36	3.85 ± 0.68	2.63 ± 0.11	**550 ± 270**
River Usumacinta				
USU2 (2012)				
2514A	0.42	0.39 ± 0.09	4.55 ± 0.17	1920 ± 20
2511*	0.84	0.51 ± 0.10	3.65 ± 0.09	**1870 ± 30**
2514B	1.14	1.17 ± 0.07	3.00 ± 0.08	1620 ± 30
2512*	1.14	1.01 ± 0.07	3.00 ± 0.08	**1670 ± 30**
2514C	1.34	1.56 ± 0.42	2.98 ± 0.11	1490 ± 140
2513*	1.50	1.16 ± 0.08	2.95 ± 0.08	**1620 ± 30**
USU13-1 (2014)				
2582A	0.2	1.50 ± 0.24	2.64 ± 0.26	1450 ± 120
2580*	0.45	1.25 ± 0.11	2.86 ± 0.16	**1570 ± 50**
2582B	0.6	0.76 ± 0.03	2.64 ± 0.26	1720 ± 40
2582C	0.8	1.09 ± 0.18	2.64 ± 0.26	1600 ± 90
2581*	1.1	1.69 ± 0.07	2.93 ± 0.14	**1430 ± 40**
2582D	1.4	3.96 ± 1.05	2.64 ± 0.26	520 ± 450
USU13-2 (2014)				
2583*	0.25	0.77 ± 0.05	2.45 ± 0.14	**1700 ± 30**
2586A	0.5	1.06 ± 0.78	2.64 ± 0.26	1610 ± 300
2586B	0.7	1.00 ± 0.03	2.64 ± 0.26	1640 ± 50
2586C	1.0	0.24 ± 0.02	2.64 ± 0.26	1920 ± 10
2584*	1.25	1.54 ± 0.07	2.38 ± 0.14	**1360 ± 50**
2586D	1.5	14.23 ± 11.68	2.64 ± 0.26	3370 BC ± 4480
2585*	1.75	0.68 ± 0.05	2.60 ± 0.16	**1750 ± 30**
2586E	2.0	0.47 ± 0.06	2.64 ± 0.26	1840 ± 30
2586F	2.2	1.07 ± 0.47	2.64 ± 0.26	1610 ± 180

*Age calculated using the full OSL dating method, in the rest of cases the Profiling method was used.

Table 3. Laboratory profiling results in the equivalent doses (Gy) obtained for aliquot 1 and aliquot 2. Aliquots consisted in ~200-300 grains of quartz stimulated in Blue. Variation between aliquot 1 and 2 is generally more than 1 Gy except for the six samples highlighted in bold. Note that the difference in the equivalent dose of the aliquot 1 and 2 is especially high in sample SUTL2586D.

SUTL	Depth (cm)	Equivalent dose (Gy)	
		Aliquot 1	Aliquot 2
2510A	18	5.99 ± 0.25	7.02 ± 1.00
2510B	88	7.64 ± 1.97	5.03 ± 0.62
2510C	118	3.91 ± 0.57	6.01 ± 2.99
2514A	**42**	**0.48 ± 0.06**	**0.30 ± 0.04**
2514B	**114**	**1.24 ± 0.12**	**1.10 ± 0.11**
2514C	134	1.14 ± 0.13	1.98 ± 0.13
2582A	20	1.74 ± 0.04	1.26 ± 0.07
2582B	**60**	**0.79 ± 0.04**	**0.74 ± 0.03**
2582C	80	0.90 ± 0.03	1.27 ± 0.05
2582D	140	5.01 ± 0.34	2.91 ± 0.21
2586A	170	0.28 ± 0.04	1.84 ± 0.12
2586B	**150**	**0.96 ± 0.12**	**1.03 ± 0.09**
2586C	**120**	**0.22 ± 0.03**	**0.26 ± 0.02**
2586D	70	25.9 ± 0.52	2.55 ± 0.16
2586E	**20**	**0.41 ± 0.05**	**0.53 ± 0.05**
S586F	0	1.53 ± 0.08	0.6 ± 0.05



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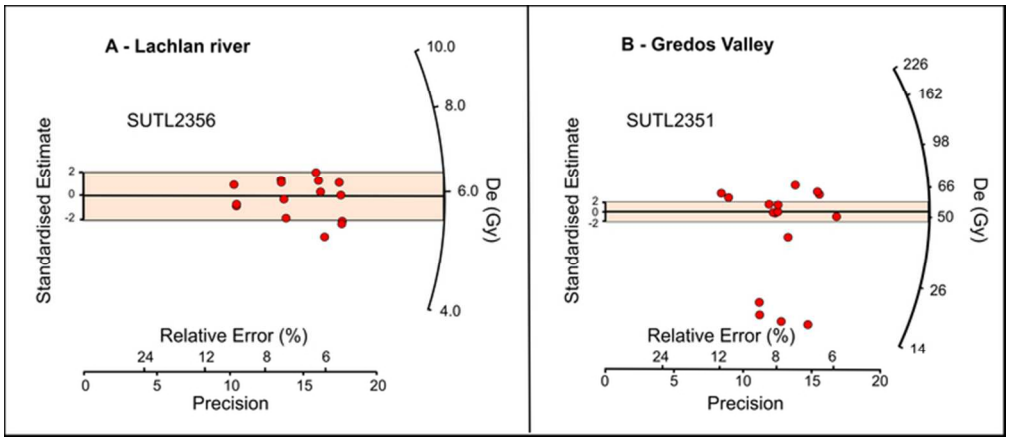

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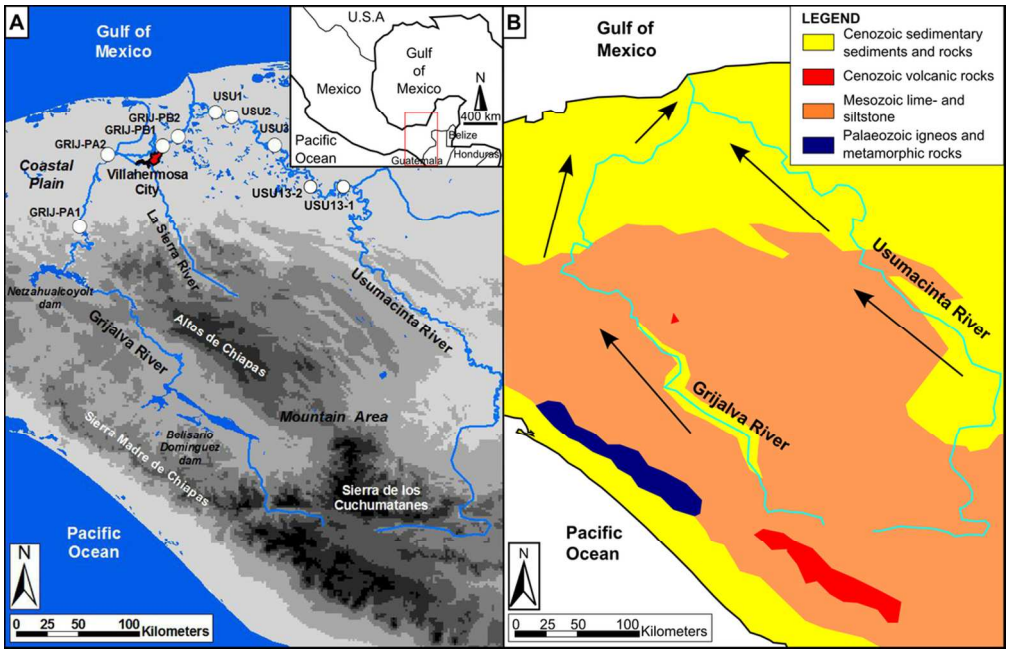

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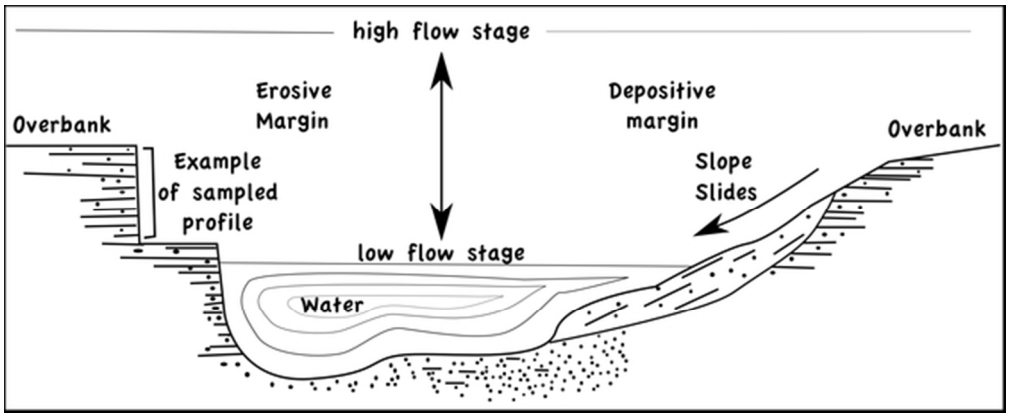

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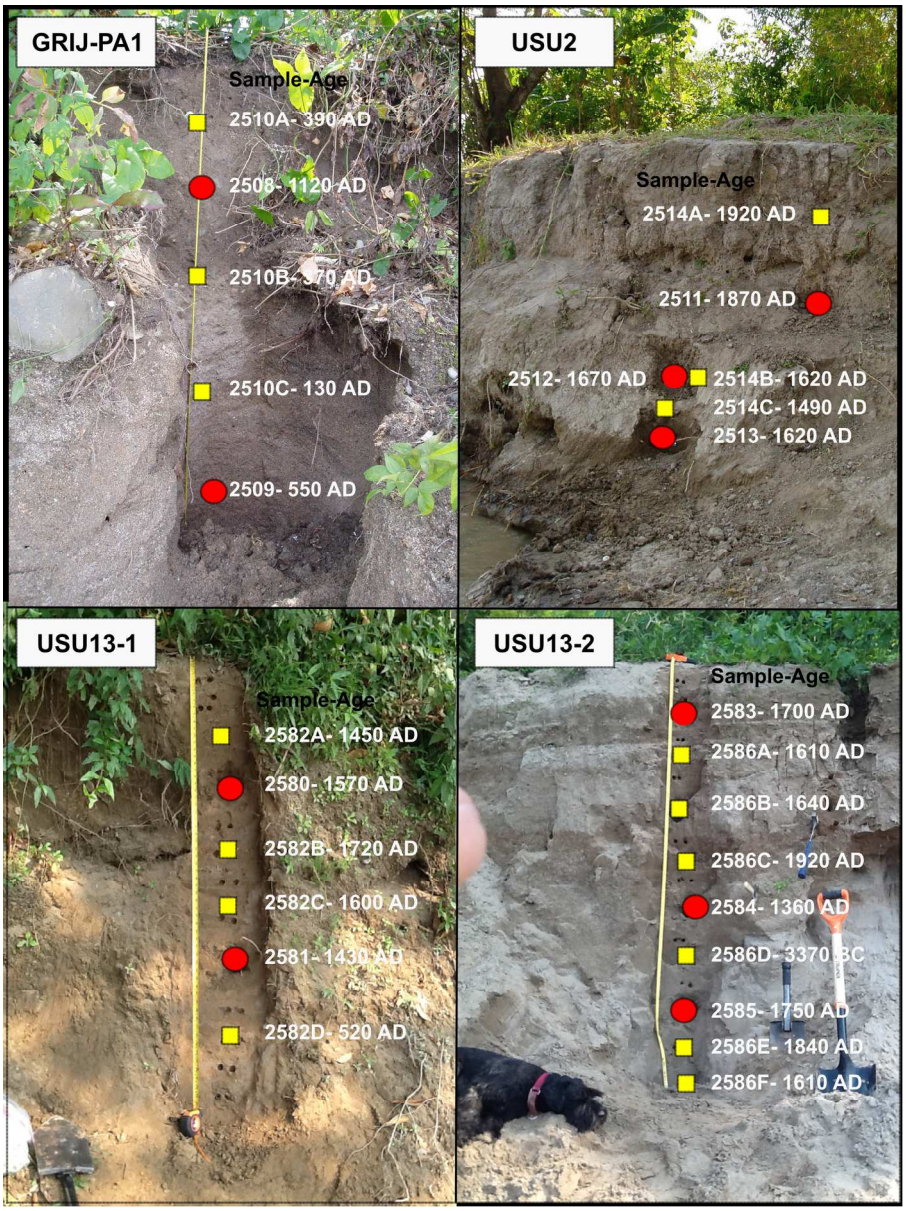

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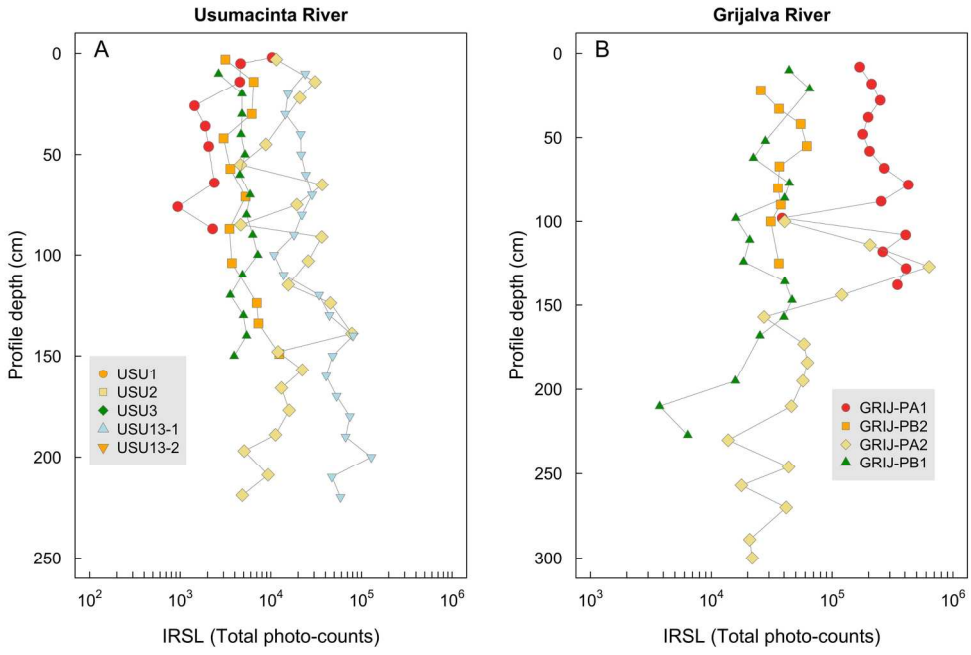

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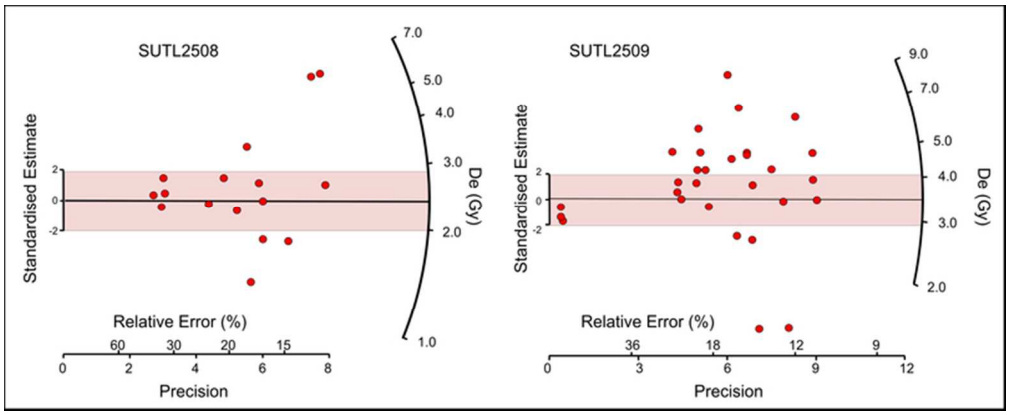

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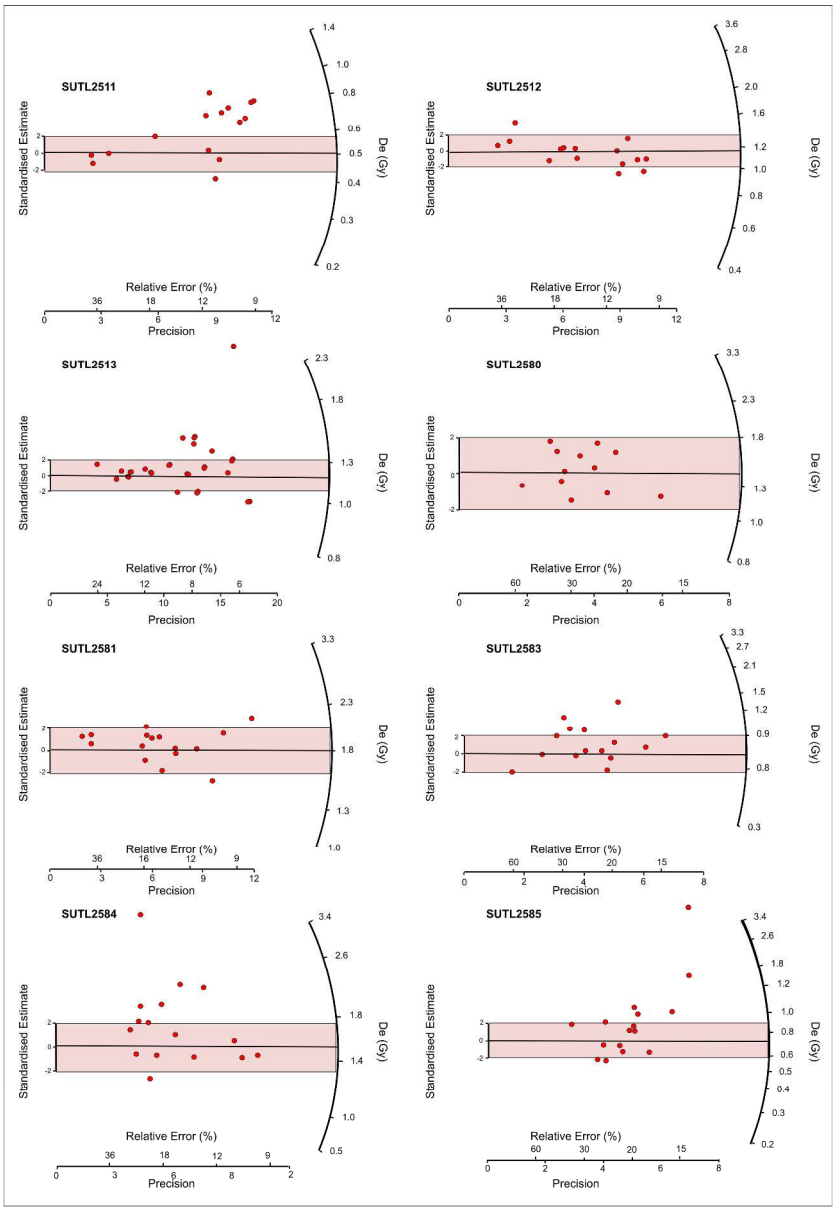

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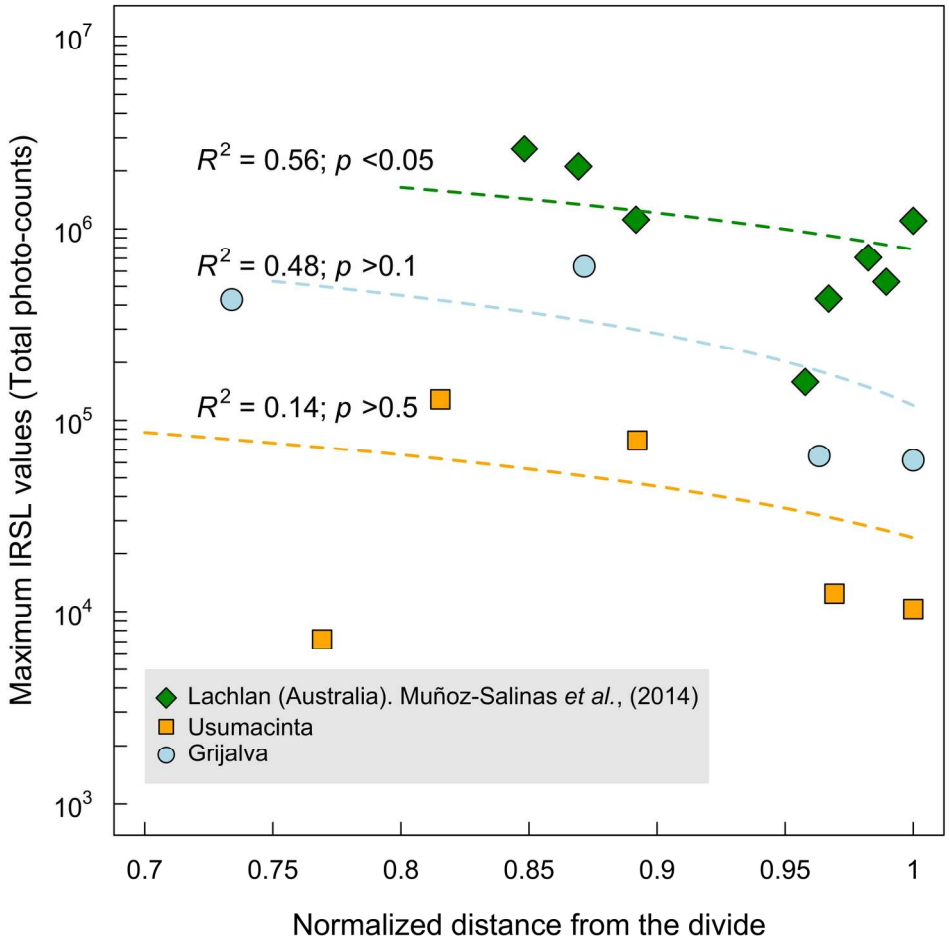

177x177mm (300 x 300 DPI)